Impact of Glazing on Growing Compartment Fires

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OUTLINE

I. Problem Statement
- Pre-Flashover Fires
- Window Breaking

II. Small Fatal Fires
- **CO**
- Filling
- Solution: Better Detection

III. Glass Breaking in Compartment Fire
- Example of Its Critical Importance

IV. Glass Breaking Physics
- Mechanism
- Radiation
- Analyses
- Results

V. Needed Research
- Glass Properties
- Heat Transfer
- GLASS FALL-OUT

Window Breaking
Is Critical
To Growth
To Flashover

Materials
Box

e-Flashover
Fires also kill:
1) CO
2) Filling

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CARBON MONOXIDE FORMATION IN FIRES BY HIGH-TEMPERATURE ANAEROBIC WOOD PYROLYSIS

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Building fire fatalities often occur at locations remote from the room where the fire is actually burning. The majority of these fire deaths are the result of smoke inhalation, primarily due to exposure to carbon monoxide (*CO*). Although causing nearly 2500 deaths per year in the United States, the mechanisms for the formation of *CO* in building or enclosure fires remain poorly characterized.

In order to test the hypothesis that high concentrations of CO can be generated by pyrolysis of wood in a high-temperature, vitiated environment, a series of natural gas fires, ranging from 40 to 600 kW in heat release rate, were burned inside a reduced-scale enclosure (RSE). The ceiling and upper walls of the RSE were lined with 6.4-mm-thick plywood. During each burn, the concentrations of CO, CO_2, and O_2 were monitored at two locations within the upper layer. Oxygen calorimetry was used to monitor the total heat release rate for each fire. Vertical temperature profiles for two positions within the enclosure were also recorded.

Much higher levels of *CO* were generated with the wood-lined upper layer than with comparable fires fueled only by natural gas. Volume concentrations as high as 14% were observed. The fires with wood in the upper layer had higher heat release rates and depressed upper-layer temperatures. The major conclusions of this work based on the experimental findings are (1) the pyrolysis of wood in a highly vitiated, high-temperature environment can lead to the generation of very high concentrations of *CO* in enclosure fires; (2) the overall wood pyrolysis is endothermic for the experimental conditions studied; and (3) the maximum mass loss rate of wood under the experimental conditions is on the order of 10 $gs^{-1}\,m^{-2}$ with the majority of released carbon being converted to a roughly 1:1 mixture of CO and CO_2.

Introduction

The majority of fire deaths within buildings [1] occur as the result of smoke inhalation from "flashed over" [2] fires at locations remote from the fire itself. Postmortem analysis of fire victims [3] as well as studies of the causes of fire death reported by medical examiners [4] indicate that roughly two-thirds of all building fire deaths are the direct result of exposure to the carbon monoxide (*CO*) generated by the fire. Although this represents nearly 2500 deaths per year in the United States [5], very few systematic investigations of CO formation during enclosure fires have been reported, and *the* mechanism(s) **for** *generating* CO in such fires remain poorly characterized.

Earlier idealized experiments [6–8] in which fires burning in an open laboratory were quenched upon entering a hood containing combustion gases showed that concentrations of the combustion gases, including *CO* and fuel, could be correlated in terms of the global equivalence ratio (GER), ϕ_g, which is defined as the mass of material in the upper layer derived from fuel divided by the mass of material derived from air normalized by the fuel to air ratio required for stoichiometric burning. The existence of these correlations has been termed the "global equivalence ratio concept" [9].

Gottuk et al. [10] demonstrated that the concentrations of combustion species generated within an enclosure carefully designed to create an environment similar to the hood experiments were also well correlated with ϕ_g, even though the correlations differed slightly from the hood results due to higher upper-layer temperatures in the enclosure fires. Work reported by Bryner et al. [11] and discussed by Pitts [12] demonstrated that the GER concept can breakdown when air is entrained directly into the upper layer of an enclosure with a single doorway. Even in the latter case, however, observed CO concentrations for underventilated burning were only 50% higher than predicted by the GER concept.

In 1987 in Sharon, PA, there was a fatal townhouse fire, where deaths occurred on the second floor, even though the fire was essentially localized in a first floor kitchen. One of the victims had an extraordinarily high level of carboxyhemoglobin, suggesting exposure to very high concentrations of *CO*. Levine and Nelson [13] investigated this fire in detail and

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SALT WATER MODELING OF FIRE INDUCED FLOWS IN MULTICOMPARTMENT ENCLOSURES

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Salt water modeling is used to study fire-induced flows in multicompartment structures. Scaling laws relating salt water flows and hot gas flows are developed. Results from 1/20 scale salt water simulations of fire-induced flows in a single-story multiroom structure are shown to be in good agreement with available full-scale results. Experiments involving a 1/20 scale model of a U.S. Navy ship demonstrate the feasibility of using the technique to study hot gas flows in compartmented structures too complex to study economically by other means.

Introduction

A major threat to the safety of inhabitants of many multiroom and multistory structures containing a localized fire is the rapid flow of combustion products throughout the structure. The paths of these flows are often complex; for example, through a series of connecting doorways, halls, stairs, shafts, etc. The time-dependent position of the hot layer fronts, layer thicknesses, and concentrations are needed to assess the threat to life safety along these complex paths.

Several alternative approaches can be considered to elucidate and understand fire generated flows in complex structures. Full-scale experiments offer the most realistic approach, but they are expensive and difficult to instrument and analyze. Drastically reduced-scale fire experiments can reduce cost, but present the same instrumentation problems as in full-scale and introduce scaling questions arising from low Reynolds number phenomena. In principle, mathematical solution of the partial differential equations of fire and flow physics should enable the determination of fire phenomena in enclosures. But issues of turbulence modeling are not fully resolved and three-dimensional unsteady flow in complex geometries is still not practical using even the largest available computers. Less fundamental mathematical lumped-parameter or "zone" models[1] reduce the mathematical complexity of the multi-compartment problem by treating the structure as a limited number of connected spatial zones. Their solution is amenable to common computers, but with no guarantee to their physical accuracy or completeness. Indeed, mixing between zones is only partially addressed, and no explicit attention is given to the time-dependent development of horizontal flows in large rooms and long corridors, and the development of vertical flows in tall shafts. One approach that physically models most of the flow characteristics and provides a clean environment for measurement with excellent flow visualization is the hydraulic analog technique known as salt water modeling. Moreover, this technique provides a relatively inexpensive approach for evaluating complex structures.

Salt water modeling substitutes turbulent buoyant salt water moving in fresh water for turbulent buoyant hot gas moving in cold gas. Since the driving phenomena for the two processes are identical—buoyancy forces resulting from density differences—the two processes can be related when viscous and heat transfer effects are small. Although this technique offers great potential in fire modeling, it has neither been used much nor has it been well documented. Thomas et al[2] used the salt water technique to show the effect of roof and side vents on clearing smoke from large rooms. Tangren et al[3] applied the technique at 1/3 scale to study the densities and positions of hot gas layers produced by fires in a room with a doorway or window vent.

The current study was motivated by the desire to evaluate smoke movement in naval combat ships. The availability from the U.S. Navy of detailed 1/20 scale clear plastic ship models and large water tanks for laboratory testing presented a natural application for

Problem:

Pre-Flashover Fires Also Kill

Solution:

Better Residential CO and Smoke Detection

Case Studies in Fire Safety Engineering Science

Assignment #1 **Case I**

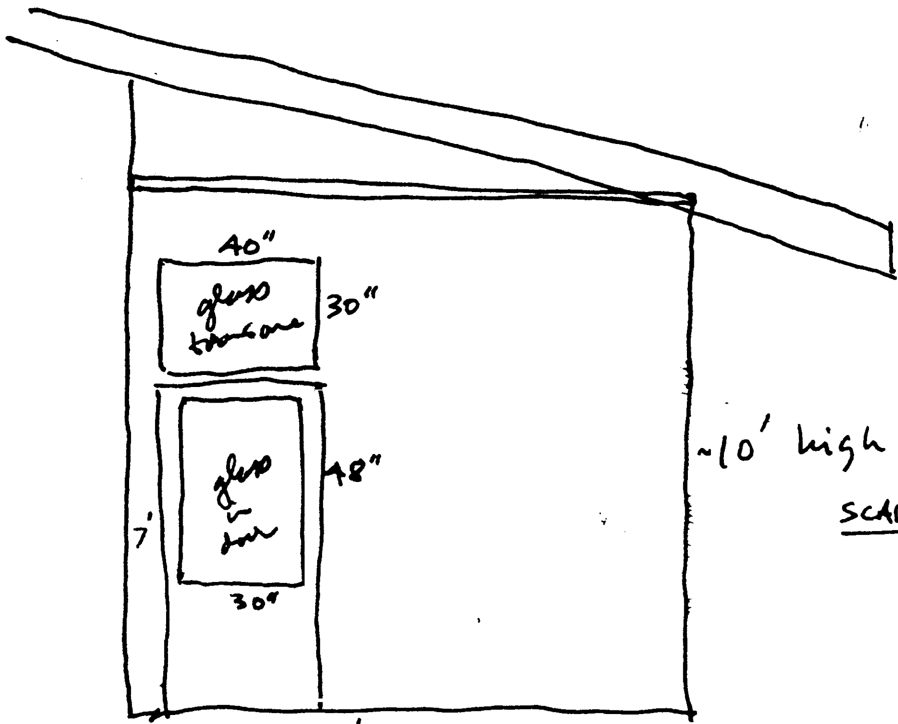
In 1983, in a small town south of San Francisco, a teacher spent an evening with friends. At 11 p.m., she returned to her room and went to bed. Because it was a cold night, she turned up the controls on her electric blanket. At 2 a.m., the local fire department received an urgent call to transport a burn victim from her address. As they pulled out of the fire station, the driver reported seeing flames at the school, a half mile away. When they arrived, an estimated ten minutes after ignition, they found a fully-involved one bedroom apartment fire (see Figs. 1-3) and the teacher with severe burns over 70% of her body. Water was applied to the fire within two minutes of arrival and suppression took less than another two minutes.

Because of the severity of the burns, it was not possible to interview the victim until four months after the fire. The initial fire department report listed the cause as "under investigation" but specifically stated "no flammable liquids were noted." The friends, whom she had been with earlier in the evening, gave the following statement:

> "She came running up to our building with 5 or 6 small fires on her body – the biggest on her shoulders and head. I hugged her and patted her back and then threw her against the door. She hit it and most of the back fire went out… She said 'kill me, kill me' obviously in great pain.. .She said her throat hurt badly and that her blanket had just 'exploded into flames'. ..I called the ambulance immediately."

Post-fire insurance company investigators eliminated other electrical appliances as the cause of ignition. This type of electric blanket is no longer manufactured in the U.S. From later interviews and depositions, the time line in Table I was estimated.

use std gyp-board R-7 walls as room average.



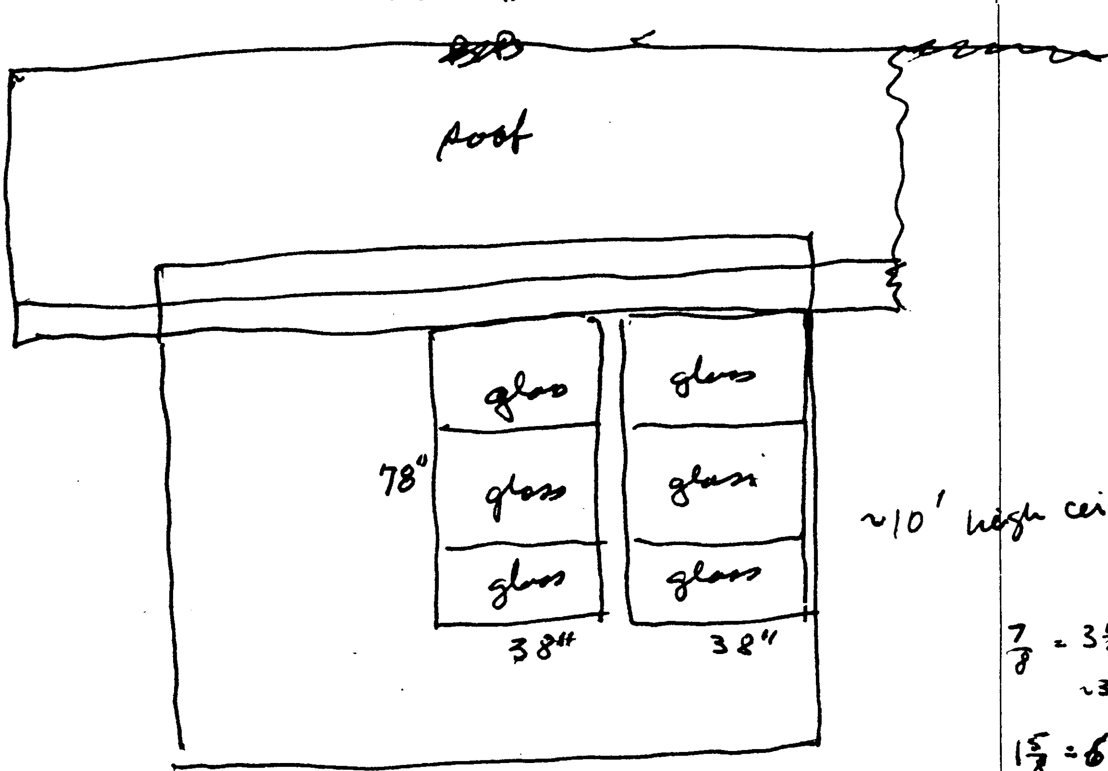
~10' high ceiling.

SCALE 1" = 4'

$\frac{5}{8}$ = 30"

1" = 48"

11½' BB↑



~10' high ceil

$\frac{7}{8}$ = 3½'

~38

$1\frac{5}{8}$ = 6½'

13'

AA↑

Fig 2

≈ 12'x16'x10' high

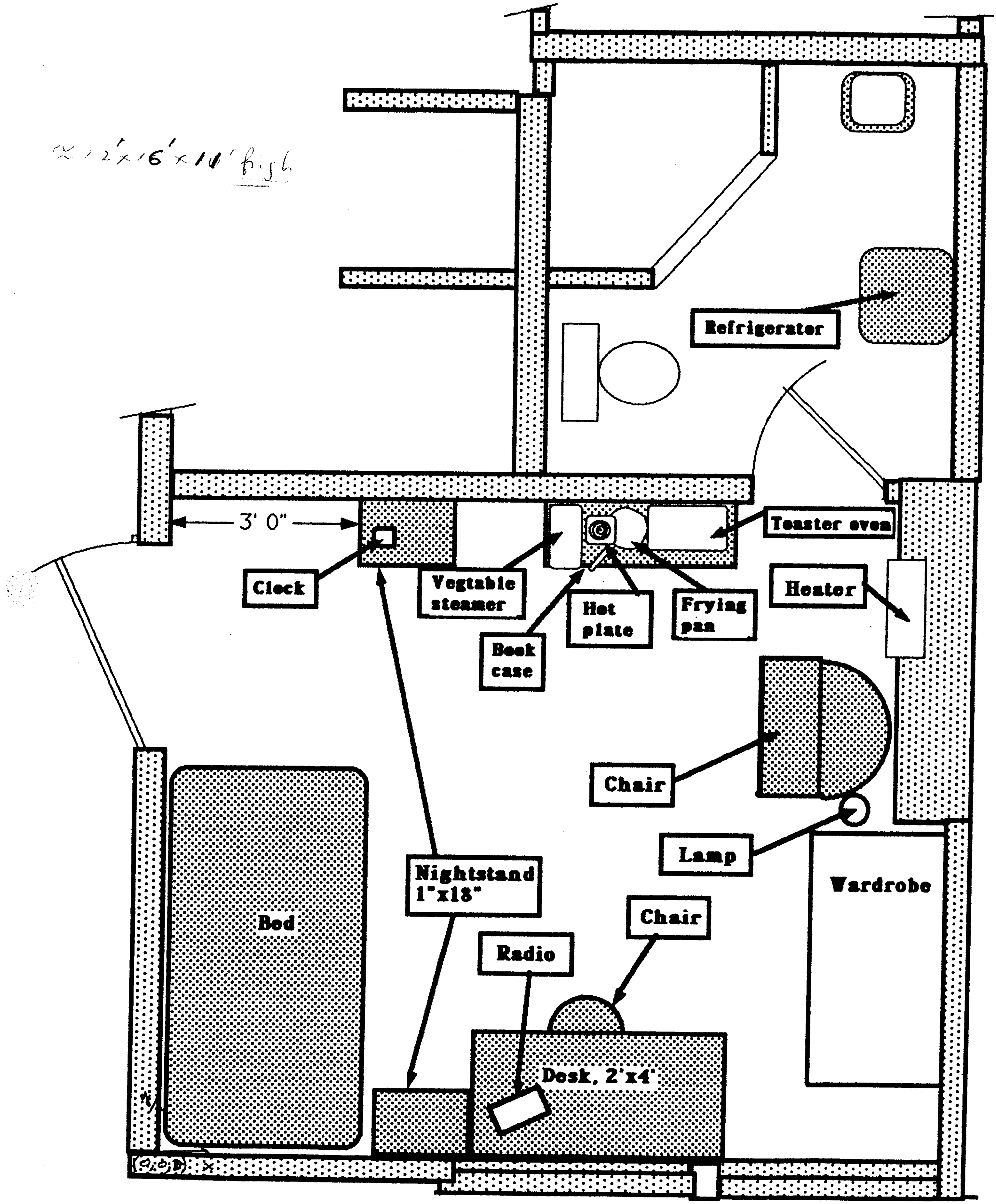
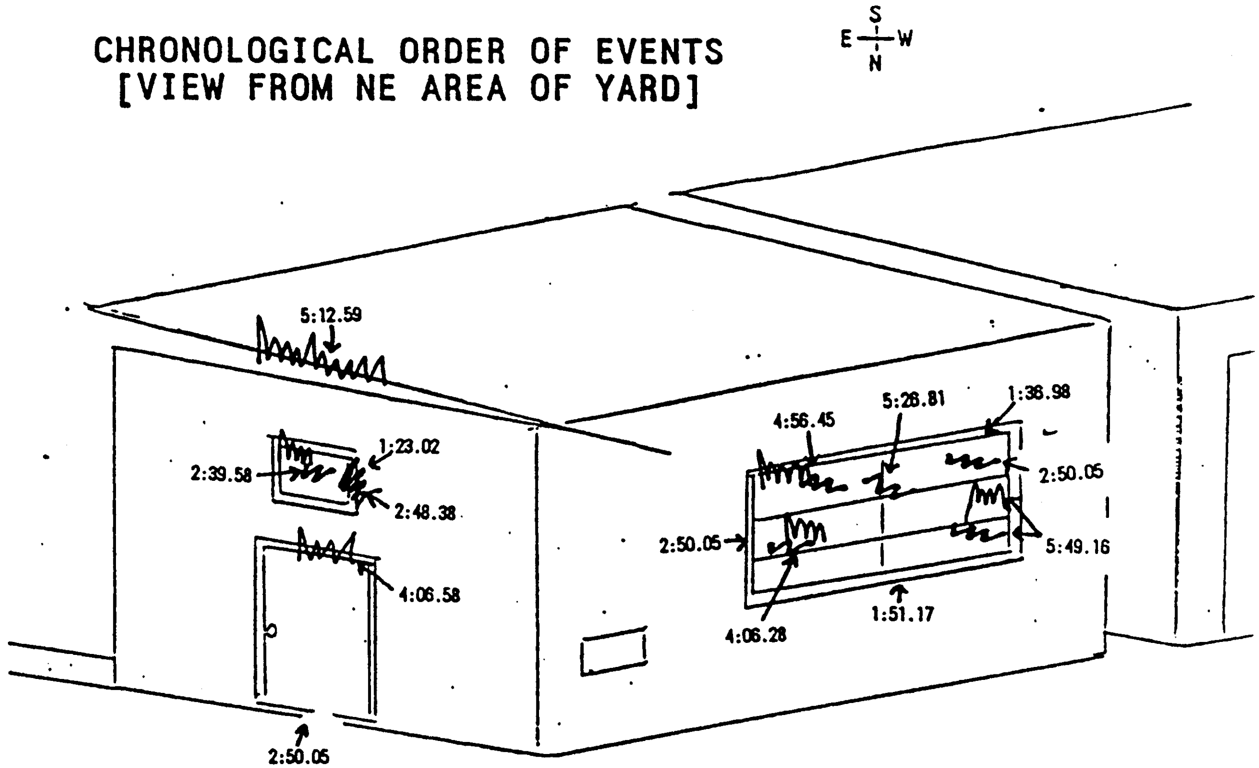


Fig. 3

FULL SCALE BURN TESTING
6/16/89

CHRONOLOGICAL ORDER OF EVENTS
[VIEW FROM NE AREA OF YARD]

1:23.02	FIRST SMOKE DETECTED - SW EDGE OF WINDOW OVER DOOR & SE EDGE OF DOOR FRAME
1:36.98	SMOKE SEEN IN SW CORNER OF MAIN WINDOW & ENTIRE TOP EDGE OF DOOR FRAME
1:51.17	SMOKE SEEN ENTIRE BOTTOM EDGE OF MAIN WINDOW FRAME
2:39.58	FIRST FLAMES SEEN INSIDE WINDOW OVER DOOR - SW CORNER
2:40.02	FLAMES SEEN ON CURTAINS INSIDE WINDOW - SE CORNER OF MAIN WINDOW
2:48.38	FIRST GLASS BREAKS IN SE CORNER OF WINDOW OVER DOOR
2:50.05	MAIN WINDOW CRACKS - SW CORNER FLAMES DETECTED OUTSIDE WINDOW
2:50.05	FLAMES COMING OUT OF WINDOW OVER DOOR - ENTIRE TOP EDGE
	TREMENDOUS AMOUNT OF SMOKE COMING FROM EACH CRACKED GLASS AREA & AROUND DOOR AND WINDOW FRAMES
3:08.95	FIREMEN OPEN DOOR TO ROOM
4:06.28	GLASS BREAKS EAST CENTER OF MAIN WINDOW - FLAMES VISIBLE
4:56.45	GLASS BLOWS OUT OF SE SECTION OF MAIN WINDOW - LARGE FLAMES COME OUT OF [illegible] ROOF OVER WINDOW & DOOR ON FIRE
5:12.59	ROOF ABOVE DOOR ENGULFED IN FLAMES
5:28.81	LARGE EXPLOSION OF GLASS BLOWING OUT OF MAIN WINDOW
	FLAMES AT HIGHEST POINT NOW
	FLAMES EXTEND OVER TO SHED OPPOSITE MAIN WINDOW AND THE EXPLOSION BLEW OUT THE GLASS IN THE SHED DOOR
5:49.16	GLASS BREAKS IN NW CORNER OF MAIN WINDOW - FLAMES CONTINUE TO SHOOT OUT
7:01.58	DOOR FALLS OFF ONE HINGE - HANGING BY THE OTHER HINGE & BADLY BURNED
9:06.24	FIREMEN APPLY WATER THROUGH DOOR
9 24 28	FIREMEN APPLY WATER THROUGH MAIN WINDOW
[illegible]	[illegible] ROOM WITH HOSES
[illegible]	[illegible] ROOM
	FLAMES STILL VISIBLE ON ROOF OVER DOOR
17:11.24	FIRE OUT - FIREMEN INSPECT PREMISES



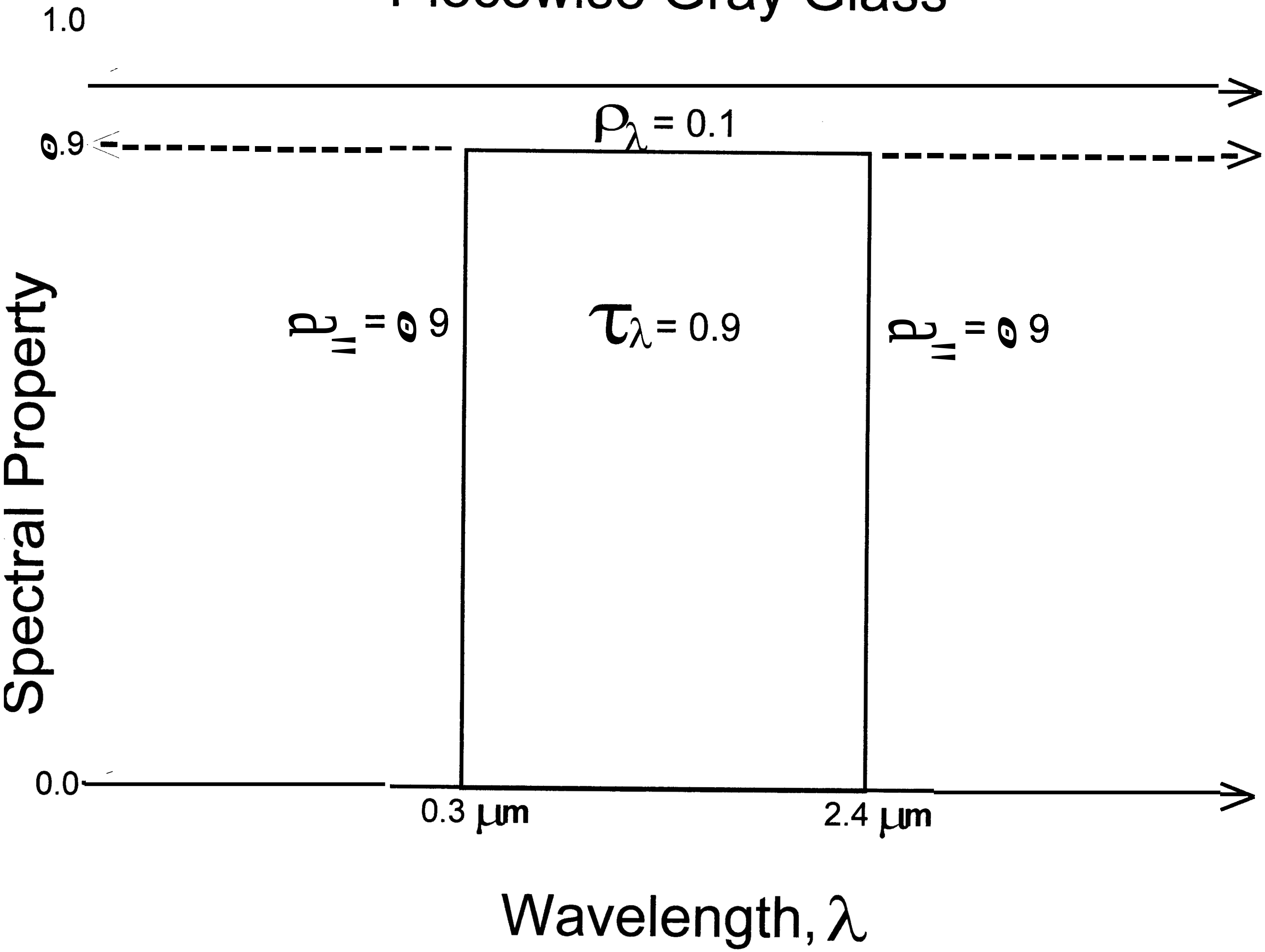
SMOKE

FIRE

GLASS BREAKING

RELATIVE HUMIDITY 42%

Piecewise Gray Glass



This simple, yet important, result is termed the *Stefan–Boltzmann law.* It enables calculation of the amount of radiation emitted in all directions and over all wavelengths simply from knowledge of the temperature of the blackbody. Because this emission is diffuse, it follows from Equation **12.14** that the total intensity associated with blackbody emission is

$$I_b = \frac{E_b}{\pi} \qquad (12.29)$$

12.3.4 Band Emission

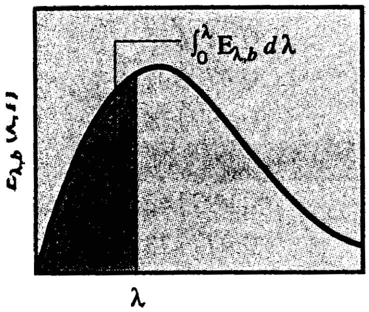


FIGURE 12.14 Radiation emission from a blackbody in the spectral band 0 to A.

It is often necessary to know the fraction of the total emission from a blackbody that is in a certain wavelength interval or *band.* For a prescribed temperature and the interval from 0 to A, this fraction is determined by the ratio of the shaded section to the total area under the curve of Figure **12.14.** Hence

$$F_{(0\rightarrow A)} = \frac{\int_0^\lambda E_{\lambda,b}\,d\lambda}{\int_0^\infty E_{\lambda,b}\,d\lambda} = \frac{\int_0^\lambda E_{\lambda,b}\,d\lambda}{\sigma T^4} = \int_0^{\lambda T} \frac{E_{\lambda,b}}{\sigma T^5}\,d(\lambda T) = f(\lambda T) \qquad \mathbf{(12.30)}$$

Since the integrand $(E_{\lambda,b}/\sigma T^5)$ is exclusively a function of the wavelength–temperature product ***AT,*** the integral ***of*** Equation **12.30** may be evaluated to obtain $F_{(0\rightarrow\lambda)}$ as a function of only ***AT.*** The results are presented in Table **12.1** and Figure **12.15.** They may also be used to obtain the fraction of the radiation between any two wavelengths A, and A„ since

$$F_{(\lambda_1\rightarrow\lambda_2)} = \frac{\int_0^{\lambda_2} E_{\lambda,b}\,d\lambda - \int_0^{\lambda_1} E_{\lambda,b}\,d\lambda}{\sigma T^4} = F_{(0\rightarrow\lambda_2)} - F_{(0\rightarrow\lambda_1)} \qquad (12.31)$$

Additional blackbody functions are listed in the third and fourth columns of Table **12.1.** The third column facilitates calculation of the spectral intensity for a prescribed wavelength and temperature. In lieu of computing **this** quantity from Equation **12.25,** it may be obtained by simply multiplying the tabulated

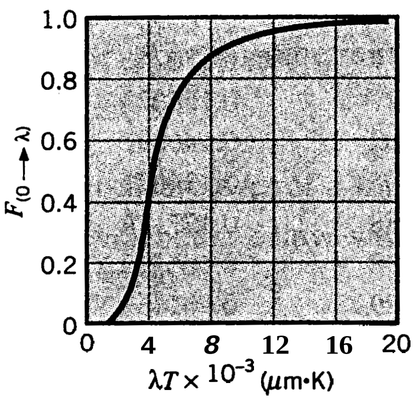


FIGURE **12.15**
Fraction of the total blackbody emission in the spectral band from 0 to A as a function of *AT.*

PIECEWISE GRAY GLASS WITH A 2.4μm CUTOFF

Temp., K	λT, μmK	Transmitted, %	Absorbed, %	Reflected, %
600	1440	1	89	10
800	1920	5	85	10
1000	2400	13	77	10
1200	2880	22	68	10
1400	3360	31	59	10

MULTIPANE PIECEWISE GRAY GLASS WINDOWS

Significant Radiation is Absorbed or Reflected at the First Fire-Side Pane

The First Pane Acts Like a Band Pass Filter only transmitting adiation which also passes through subsequent panes

Conclusion: Flam and Hot Layers do not Radiatively Heat Panes Beyond the First in Multipane Windows

Glass Breaking in Fires

Hooke's Law $\quad \text{strain} \equiv \Delta\ell / \ell \equiv \varepsilon = \dfrac{\sigma}{E}$ Tensile Stress/Modulus

$$\sigma_b \sim 5\,x\,10^{+7} \quad N/m^2$$

$$E \sim 7\,x\,10^{+10} \quad N/m^2$$

$$\varepsilon_b \sim 0.7\,x\,10^{-3}$$

$\varepsilon_b \sim 0.07\%$ strain required to break glass

Thermal Expansion

β = thermal coefficient of linear expansion
(fractional change in length per degree of temperature rise)

$\sim 9 \times 10^{-6}$ K^{-1} for glass

$\varepsilon = \beta \Delta T$ strain produced by ΔT

$$\Delta T_b = \frac{\sigma}{E\beta} \sim \frac{5x10^7}{7x10^{10} \cdot 9x10^{-6}} \sim 80°C$$

including the exponential decay of in-depth absorption of incident radiation and non-lin radiation, are presented. The stress fields produced by these temperature fields are then The article ends with suggestions for practical implementation.

2. HEATED GLASS TEMPERATURE HISTORY, T(x,t)

Consider the window shown in Fig. 1a and 1b. The goal is to calculate the temper large central section of the glass as a function of depth into the glass, x, and time, t. Sig dients, $\partial T/\partial x$, exist since the heat source is on the inside of the window and the sink is side. All symbols are defined in the nomenclature. The unshaded glass is uniformly hea and $\partial/\partial z$ are zero. The governing equation is

$$\rho c\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} + I(t)\frac{e^{-x/l}}{l},$$

where $I(t)$ is the incident radiative flux directly **from** the fire which is at suffic wavelengths that its distributed internal absorption needs to be included [11] **and** l is the c in the glass (see e.g. Fig. 2 of Ref. 12). With the assumption that the glass is grey to oth the initial and boundary conditions are

hot layer fire side surface radiation from hot layer. radiation of glass

$$at\ t = 0,\ T = T_i,$$

$$at\ x = 0, -k\frac{\partial T}{\partial x} = h_2(T_{2\infty}(t) - T(0,t)) + \varepsilon_\infty \sigma T_{2\infty}^4(t) - \varepsilon\sigma T^4(0,t) = q_2(t),$$

glass convection glass

$$at\ x = L, -k\frac{\partial T}{\partial x} = h_1(T(L,t) - T_{1\infty}(t)) + \varepsilon\sigma T^4(L,t) - \varepsilon_\infty \sigma T_{1\infty}^4(t) = q_1(t),$$

ambient

where side 1 is toward the ambient and side 2 is toward the hot layer in the compartment.

With the definitions

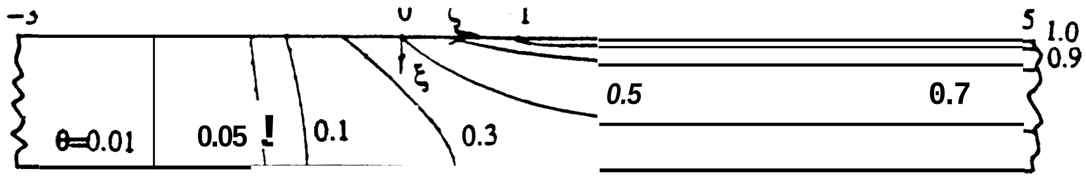
$$\xi = \frac{x}{L};\ \tau = \frac{\alpha t}{L^2};\ \gamma = \frac{l}{L};\ \theta = \frac{T - T_i}{T_c};\ T_c = \sigma_b/E\beta;\ \phi_1 = \frac{q_1}{kT_c/L};\ \phi_2 = \frac{q_2}{kT_c/L},$$

the dimensionless governing equation is

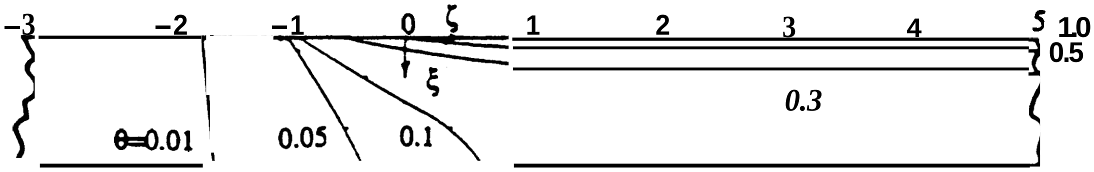
$$\frac{\partial\theta}{\partial\tau} = \frac{\partial^2\theta}{\partial\xi^2} + j(t)\frac{e^{-\xi/\gamma}}{\gamma},$$

with dimensionless initial and boundary conditions

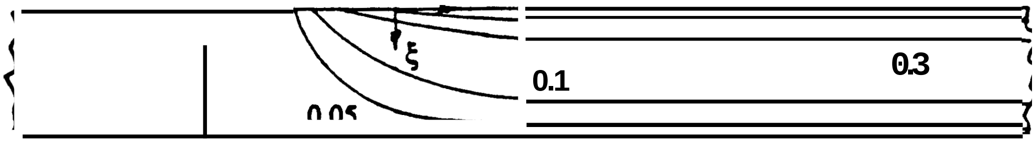
$$at\ \tau = 0,\ \theta = 0;\quad at\ \xi = 0,\ -\frac{\partial\theta}{\partial\xi} = \phi_2(\tau);\quad at\ \xi = 1,\ -\frac{\partial\theta}{\partial\xi} = \phi_1(\tau).$$



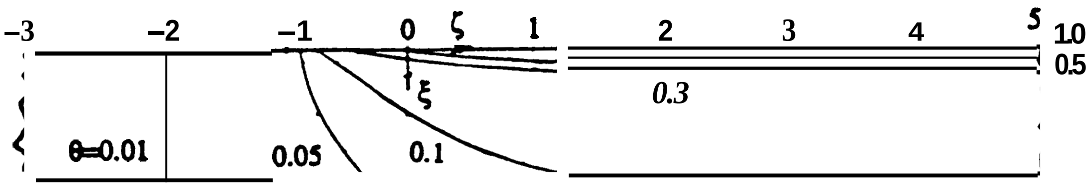
3(a)



3(b)

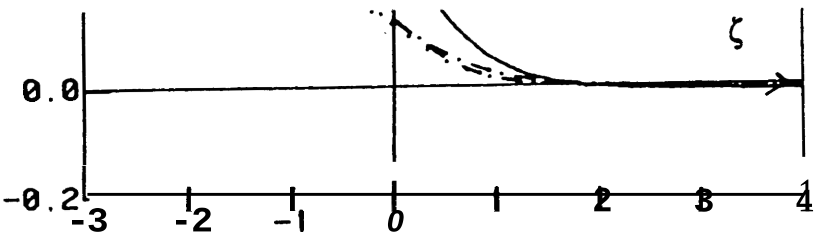


3(c)



3(d)

Fig. 3. Two-dimensional temperature contours, $\theta = (T - T_i)/(\sigma_b/E\beta)$ for times at which $\theta(0,H/L,\tau) = 1$. *a:* Fast fire next to the *window*, $\tau = 0.66$, $q_1 = 0$, $I = 5\ kW/m^2$ *and* $q_2 = 1 kW/m^2\ exp(t/30s)$. b: Medium fire next to the window, $\tau = 1.40$, $q_1 = 0$, $I = 100\ W/m^2\ exp(t/30s)$ and $q_2 = 200\ W/m^2 exp(t/30s)$.
c: Same as b, except $q \neq 0$, $\tau = 1.42$, $q_1 = 0$ for $t < 30s$ *and* $100 W/m^2\ exp((t-30s)/30s)$ for $t \geq 30s$, $I = 100 W/m^2\ exp(t/30s)$ *and* $q_2 = 200\ W/m^2\ exp(t/30s)$. *d: Slow* fire *away* from the window, $\tau = 3.17$, $q_1 = 0$ for $t < 30s$ *and* $10\ W/m^2\ exp(((t-30s)/60s)$ for $t \geq 30s$, $I = 0$ and $q_2 = 100\ W/m^2(t/60s)$.



glass breaks.

5. APPLICATION

Evaluating the dimensionless temperature field given by Eq. (32) for a large range [13] suggests that the variation of the mean temperature, N_T, with distance normal to shaded edge, ζ, can be well approximated, when the window is about to break, by tangent (see Fig. *5).* Therefore, we can reduce the application of Eq. (38) to simply t predicting the window central temperature, if we assume a hyperbolic tangent profile an

$$N_T(\zeta,\tau_b) = \frac{g}{2}\left[1+\tanh\zeta\right] \quad in \quad 1 = \frac{L}{H+s}\int_{-s/L}^{H/L} N_T(\zeta,\tau_b)\,d\zeta - N_T(-s/L,\tau_b).$$

This yields **a** geometric factor g which depends only on s/L and s/H given as

$$g = 2/[\tanh(s/L) + \ln(\cosh(H/L)/\cosh(s/L))L/(s+H)]$$

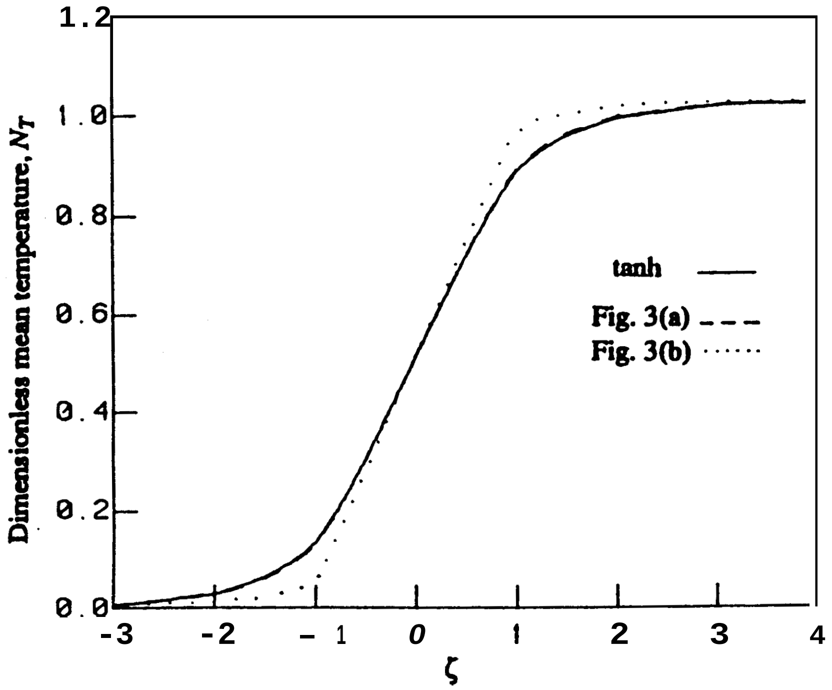


Fig. 5. Comparison of t N_T profile at breakag N_{zz} = 1, with a hype bolic tangent profile.

Figure 6 shows that **g** remains near 1 for all reasonable s/L and s/H. In the limiting temperature profile; $N_T = 0$ for $\zeta < 0$ and $N_T = g$ for $\zeta > 0$, $N_{zz} = g/(1+s/H)$ f $-g/(1+H/s)$ for $\zeta > 0$, so that $g = 1 + s/H$. The compression in the unshaded region variation in g for the step and the hyperbolic tangent profile for $s/L \geq 2$ are quite cl that the edge temperature remains close to the initial temperature (see Fig. 3). Thi

Glass Breaking in Fires

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ABSTRACT

Glass breaking in compartment fires is an important practical problem since a window acts as a wall before breaking and as a vent after breaking. If sufficient excess pyrolyzates have accumulated in the hot layer, this sudden geometric change can lead to backdraft and flashover. As Emmons explained at the First Symposium, windows break in fires due to thermal stress from the differential heating of the central portion and'the shaded edge. The focus of this paper is on quantifying the connection between the compartment fire and the glass temperature to predict the window breaking time, t_b. Techniques are presented for accurately calculating the history of the central glass temperature profile, $T(x,t)$, for any fire exposure. Two-dimensional temperature histories, $T(x,y,t)$, where x is depth and y is toward the center, and mean stress histories, $\sigma_{zz}(y,t)$, are also calculated. It is determined here that breaking occurs when the mean glass temperature difference is AT $=(\sigma_b/E\beta)g$, where σ_b/E is the maximum glass tensile strain, β is the thermal coefficient of linear expansion and g is a geometry factor of order one. Calculations suggest that the edge remains at its initial temperature, T_i, so that AT $=T(t_b)-T_i$, when the shading is large, $s/L \geq 2$, and the heating is fast, $a t_b/s^2 \leq 1$, where L is the glass thickness, s is the shaded edge width and a is the glass thermal diffusivity.

KEYWORDS: Window breaking, Glass temperatures, Compartment fire venting, Glass thermal stresses, Backdraft.

1. INTRODUCTION

Professor Emmons identified the problem of window breaking in compartment fires as an important unaddressed structural problem in his exemplar article on needed fire science at the First Symposium [1]. The mechanism he suggests for window breakage in fires is thermally induced tensile stress. All window glass has its surrounding edge covered by an opaque frame or gasket. Since glass is a relatively poor conductor, the edge remains unheated while the fire raises the temperature of the central portion by infrared radiation and hot gas convection. The thermal expansion of the uncovered window glass places the covered edge in tension until it cracks. Once the fracture begins, it bifurcates and very quickly propagates across the window; the glass falls out, creating a new vent in the compartment. Wired glass works, not by preventing fracture, but simply by holding the broken pieces in the frame and thereby avoiding a new vent. Double pane windows take longer to break than single pane because each pane sequentially undergoes the breaking process. Tempered glass also takes longer to break since the thermally created tension must first overcome the compression

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Fire-Induced Thermal Fields in Window Glass. I—Theory

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ABSTRACT

Window glass breaking plays an important role in compartment fire dynamics as the window acts as a wall before breaking and as a vent after breaking. Previous work suggested a model for the time to breakage of a window glass exposed to a particular fire. In this paper, the glass thermal fields obtained using that model are examined in detail. The temperature field dependence on heat transfer coefficients, radiative decay length and flame radiation is explored. The results show that the glass surface temperature increases with a decrease in the decay length and increases with an increase in flame radiation heat flux. Early in the fire, the glass temperature may be higher than the hot layer temperature due to direct impingement of flame radiation. Later the glass temperature lags the hot layer temperature. The variation of the time to breakage as a function of the shading width and decay length is also presented and the results indicate that the breaking time decreases with an increase in the shading width and decreases with a decrease in decay length. Heat flux maps for typical conditions indicate that most of the heat influx is stored in the glass, increasing its temperature.

NOTATION

A–G	Constants
Bi	Biot number, hL/k
c	Specific heat capacity

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a

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Fire-Induced Thermal Fields in Window Glass. 11—Experiments

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ABSTRACT

The authors' previously presented model determines the time to breakage of window glass exposed to a compartment fire. The physical and mechanical properties of glass and the history of the compartment fire are required. Among the mechanical properties of glass, the breaking stress, σ_b, is the least well known. Here, experiments on 59 plate glass samples using the four-point flexure method are described to determine the breaking stress distribution. This distribution is described by a three-parameter cumulative Weibull function, $G(\sigma_b) = 0$, for $\sigma_b < \sigma_u$ and

$$G(\sigma_b) = 1 - \exp\left(\frac{\sigma_b - \sigma_u}{\sigma_0}\right)^m \quad \text{for} \quad \sigma_b \geq \sigma_u$$

with the parameters $m = 1{\cdot}21$, $\sigma_0 = 33\ MPa$ and $\sigma_u = 35.8\ MPa$. A breaking stress of 40 MPa (5800 psi) was determined to be a reasonable value to use in breaking calculations for ordinary window glass. The breaking patterns of the test specimens suggest that fractures initiate at edge imperfections rather than at surface flaws. Some experiments to estimate the heat transfer coefficient inside the compartment and the emissivity of the hot layer are also described and values are suggested for use in the model.

NOTATION

a	Distance between points of load application in flexure test
b	Width of the glass specimen

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Users' Guide to BREAK1, The Berkeley Algorithm for Breaking Window Glass in a Compartment Fire

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PHYSICAL AND MECHANICAL PROPERTIES OF GLASS

1.Thermal conductivity [W/mK]= .7600E+00
2.Thermal diffusivity [m^2/s]= .3600E-06
3.Absorption length [m]= .1000E-02
4.Breaking stress [N/m^2]= .4700E+08
5.Youngs modulus [N/m^2]= .7000E+11
6.Linear coefficient of expansion [/deg C]= .9500E-05

GEOMETRY

1.Glass thickness [m]= .0064
2.Shading thickness [m]= .0150
3.Half-width [m]= .5000

COEFFICIENTS

1.Heat transfer coeff, unexposed [W/m^2-K]= 10.00
2.Ambient temp, unexposed [K]= 300.0
3.Emissivity of glass = 1.00
4.Emissivity of ambient (unexposed) = 1.00

FLAME RADIATION

Number of points used for flux input: 2

point #	time [s]	flux [W/m^2]
1	.00	.00
2	1000.00	.00

GAS TEMPERATURE

Number of points used for temperature input: 17

point #	time [s]	temperature [K]
1	.00	300.00
2	10.00	303.30
3	20.00	303.96
4	30.00	304.60
5	40.00	305.57
6	50.00	306.85
7	60.00	308.20
8	70.00	310.09
9	80.00	312.64
10	90.00	315.50
11	100.00	319.56
12	110.00	325.19
13	120.00	331.73
14	140.00	353.71
15	160.00	388.29
16	180.00	437.97
17	200.00	831.07

HEAT TRANSFER COEFF. ON HOT LAYER SIDE

Number of points used for heat transfer coeff input: 2

point #	time [s]	h2 [W/m^2-K]
1	.00	50.00
2	1000.00	50.00

EMISSIVITY OF HOT LAYER

Number of points used for emissivity input: 2

point #	time [s]	emissivity
1	.00	1.00
2	1000.00	1.00

NUMERICAL PARAMETERS

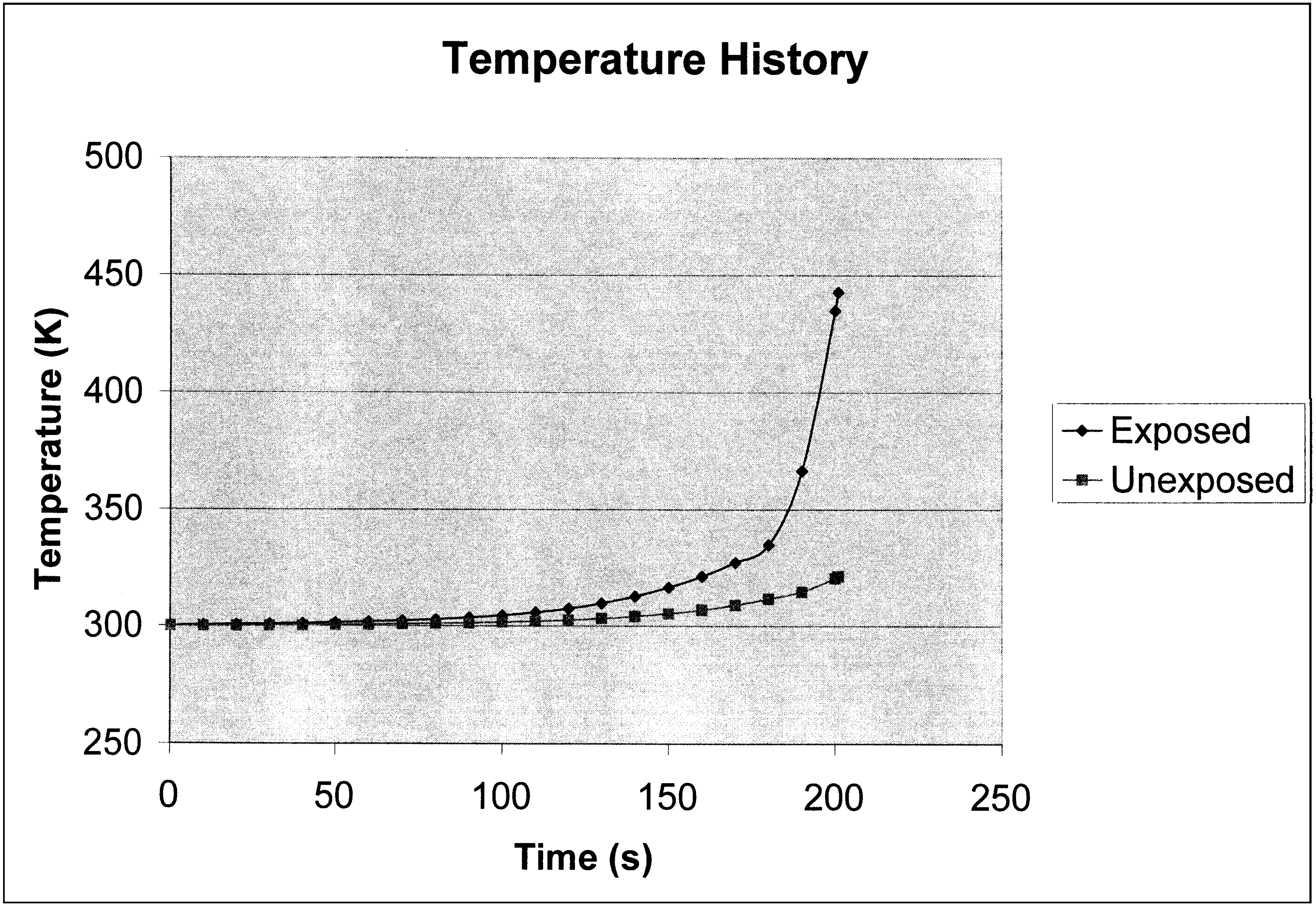
1.Maximum fractional error in soln= .000100
2.Size of time step [s]= 1.000
3.Maximum run time [s]= 250.00
4.Time interval for output [s]= 10.00

TEMPERATURE HISTORY

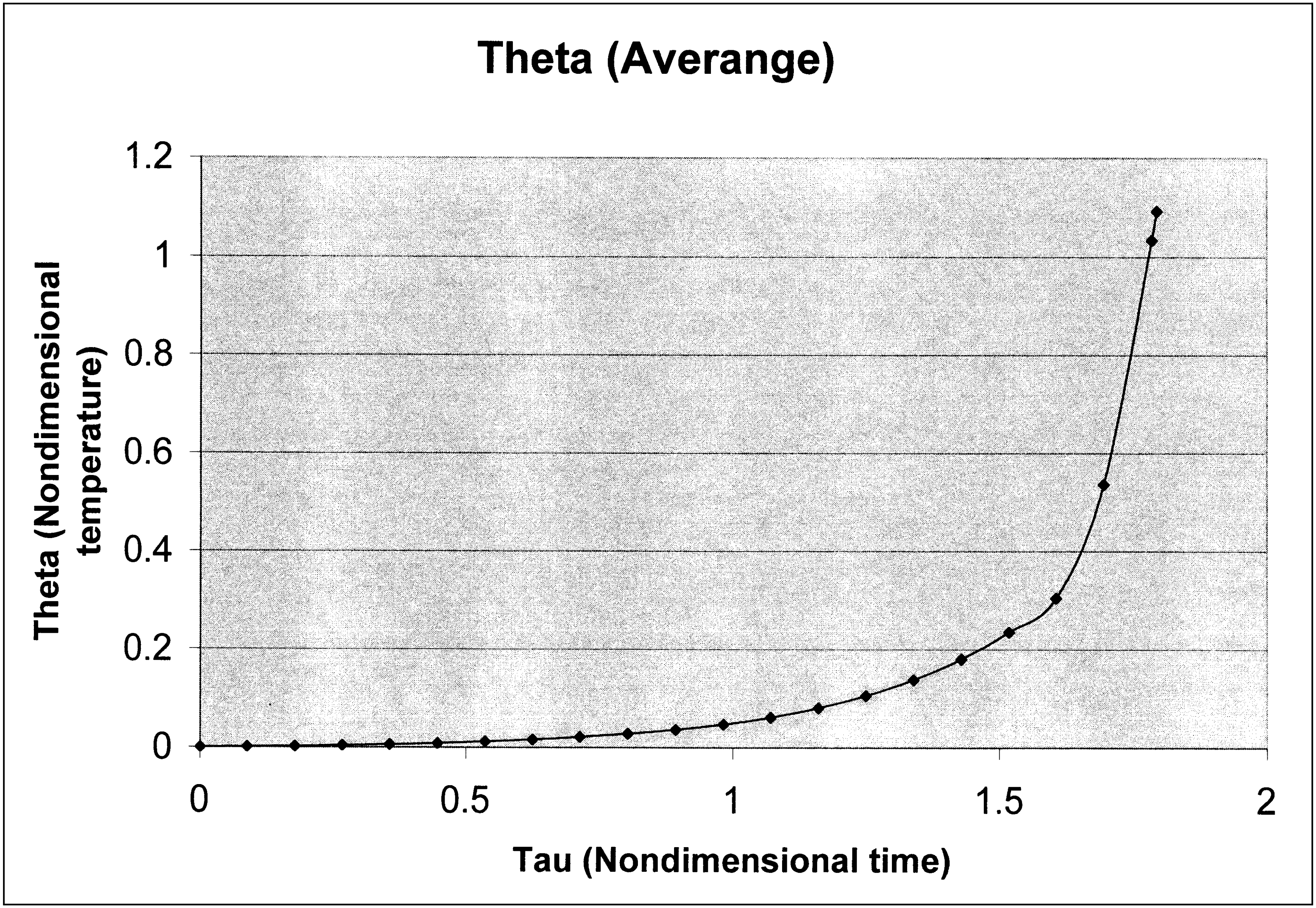
Time (s)	Exposed T(K)	Unexposed T(K)	Theta (Average	Tau
.0	300.0	300.0	.000	.000
10.0	300.3	300.0	.001	.089
20.0	300.6	300.0	.002	.179
30.0	300.8	300.1	.004	.268
40.0	301.1	300.2	.006	.357
50.0	301.4	300.4	.008	.446
60.0	301.8	300.5	.012	.536
70.0	302.3	300.7	.016	.625
80.0	302.9	301.0	.021	.714
90.0	303.7	301.2	.028	.804
100.0	304.6	301.6	.036	.893
110.0	305.9	302.0	.047	.982
120.0	307.5	302.6	.061	1.071
130.0	309.7	303.3	.080	1.161
140.0	312.6	304.2	.105	1.250
150.0	316.4	305.4	.138	1.339
160.0	321.1	307.0	.180	1.428
170.0	327.2	309.0	,235	1.518
180.0	334.7	311.6	.304	1.607
190.0	366.5	314.6	,536	1.696
200.0	434.9	320.3	1.033	1.786
201.0	442.7	321.2	1.092	1.795

Window breaks at time = 201.00 [s]

tau = t/tc, tc = 112.0 s, Avg. theta = (Tav-Ti)/Tc, Tc = 70.7 K
g = 1.039
Avg. T init = 300.0 K, Avg. Delta T = 77.2 K, Avg. T break = 377.2 K



Temperature History
Temperature (K)
500
450
400
350
300
250
0
50
100
150
200
250
Time (s)
Exposed
Unexposed


Theta (Averange)
Theta (Nondimensional temperature)
Tau (Nondimensional time)
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2

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THERMAL BREAKAGE OF DOUBLE-PANE GLAZING BY FIRE

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ABSTRACT

A model for double-pane window breakage due to heating by fire is developed that applies to both compartment fires and to urban/wildland intermix fires. This work builds on the model and computer code, BREAK1, for single-pane window breaking by fires, as described in previous publications, with additional features including the inter-pane gap heat transfer and sequential pane-breaking. A Mathcad-based computer code, McBreak, is developed that implements the double-pane model. Radiation is shown to dominate the inter-pane gap transport unless low-emissivity interior glass surfaces are used. Fires on the outdoor side of double-paned windows are included, since windows represent one of the most vulnerable features of dwellings in the urban/wildland intermix and double-paned windows help fire-harden a structure. Examples are presented for double-pane window breakage in compartment fires and wildland fires. Confirmed is the empirical observation that double-pane equipped structures might survive urban/wildland intermix fires better than their single-pane equipped neighbors.

INTRODUCTION

Windows can be important dynamic components influencing fire behavior because when they break, they change from impermeable barriers to large ventilation sources.[1,2] Further, typical breakage events occur at critical stages of fire growth, and the resulting sudden venting *can* materially alter the course of a fire—possibly resulting in backdrafts or flashover. Thus, accurate prediction of glass breakage is critical to fire modeling. In the context of the urban/wildland intermix, windows can be a point of entry for wildfire conflagrations. Observation of fire damage patterns in the 20 October 1991 Oakland Hills Fire suggest that dwellings with double-paned windows at the periphery of the fire survived while their single-paned neighbors did not.[3,4]

Thermal stress causes glass breakage?" In this paper we consider the simplest and most common geometry in which the temperature in the central area of the glass pane rises much faster than that in the protected frame-covered area. Therefore, the center expands more than the cool, frame-protected boundary. This puts the area under the frame in tension and causes early fracture because glass is brittle and its strength in tension is limited by imperfections on the edges. The glass breaks when the mean temperature, T_m, of the central pane reaches the break temperature,

$$T_{m_b} - T_i = fT_c, \tag{1}$$

where $f = 2[\tanh(s/L) + \ln(\cosh(H/L)/\cosh(s/L))L/(s+H)]^{-1}$ is a factor close to unity that accounts for the small amount of compression in the central heated panes and $T_c = \sigma_b/E\beta$ is the characteristic temperature. These results have been verified experimentally.[8,12-14] Equations (4) and (44) of Ref. [15] should be replaced with the more exact Eq. (1) above which was also given previously as Eqs. 40 and 41 of Ref. [6].

The mean temperature is approximated in terms of the surface temperatures as

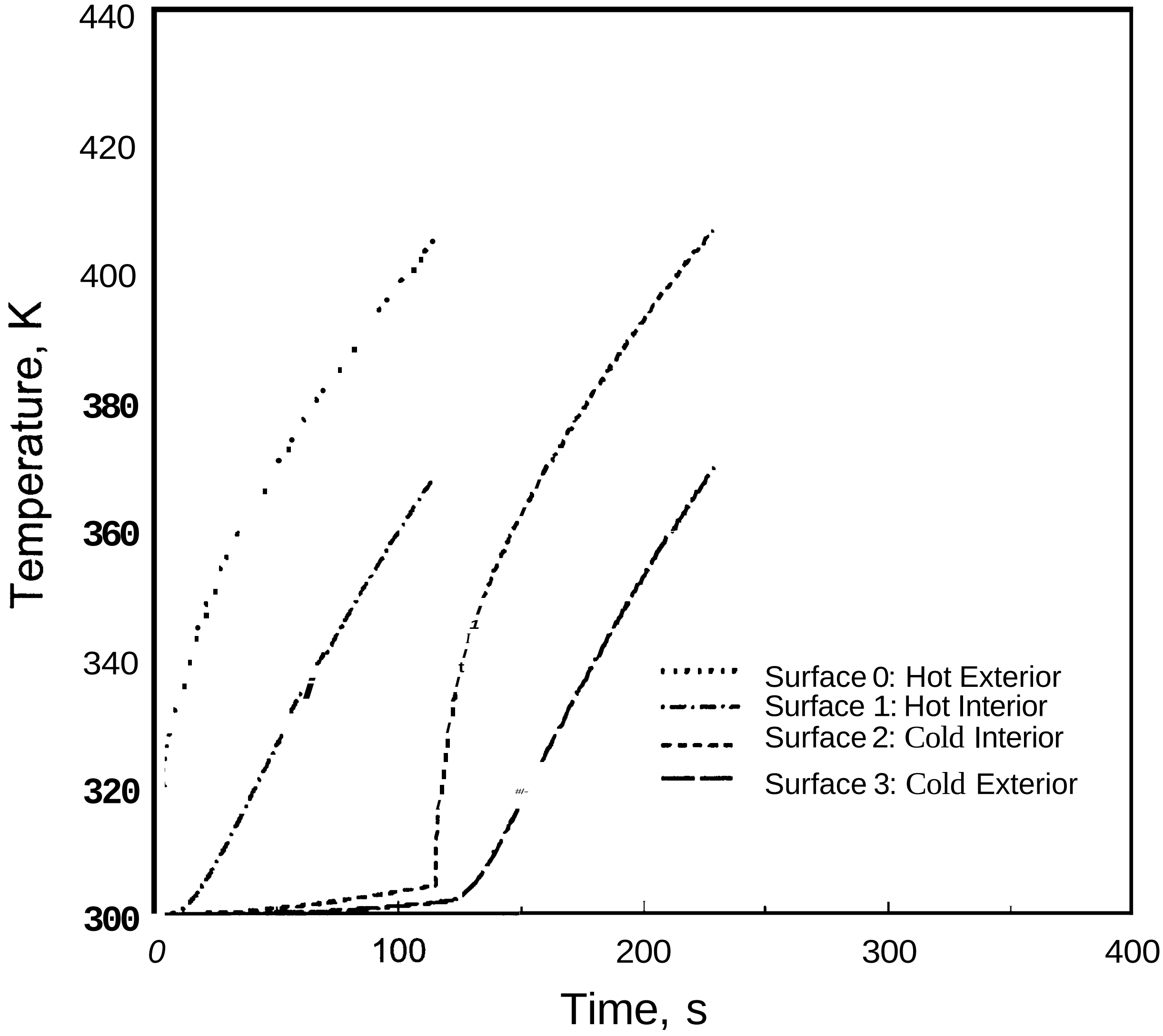


Figure 6c. Same problem **as** Fig. 6a but with $\mathscr{F}$=0.25. Both panes break.

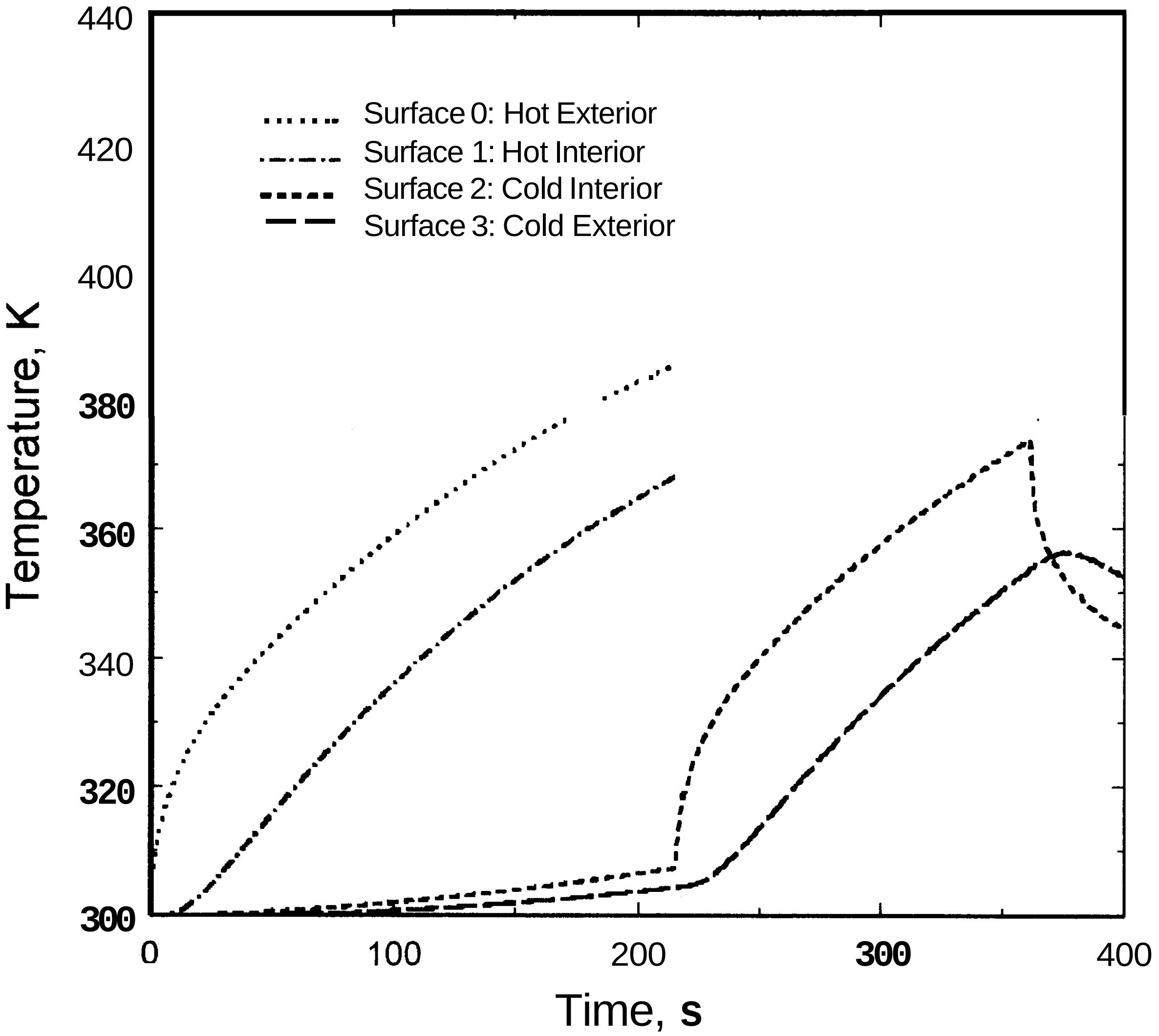


Figure 6a **Urban/wildland intermix application of double-pane window glass breakage. Outer pane** is **exposed** to **burning vegetation** at $1000K$ **for** $360s$ **Exterior radiative heating** with $\epsilon=0.15$ occurs with **simultaneous convective and radiative** ($\epsilon=0.85$) **cooling at** $300K$. **All other input parameters are the same** as **in Fig.** 5 except $h_0=50$ $watts/m^2K$, $h_{12}=2.5$ $watts/m^2K$, and $h_3=3$ $watts/m^2K$. **The cool pane does not break.**

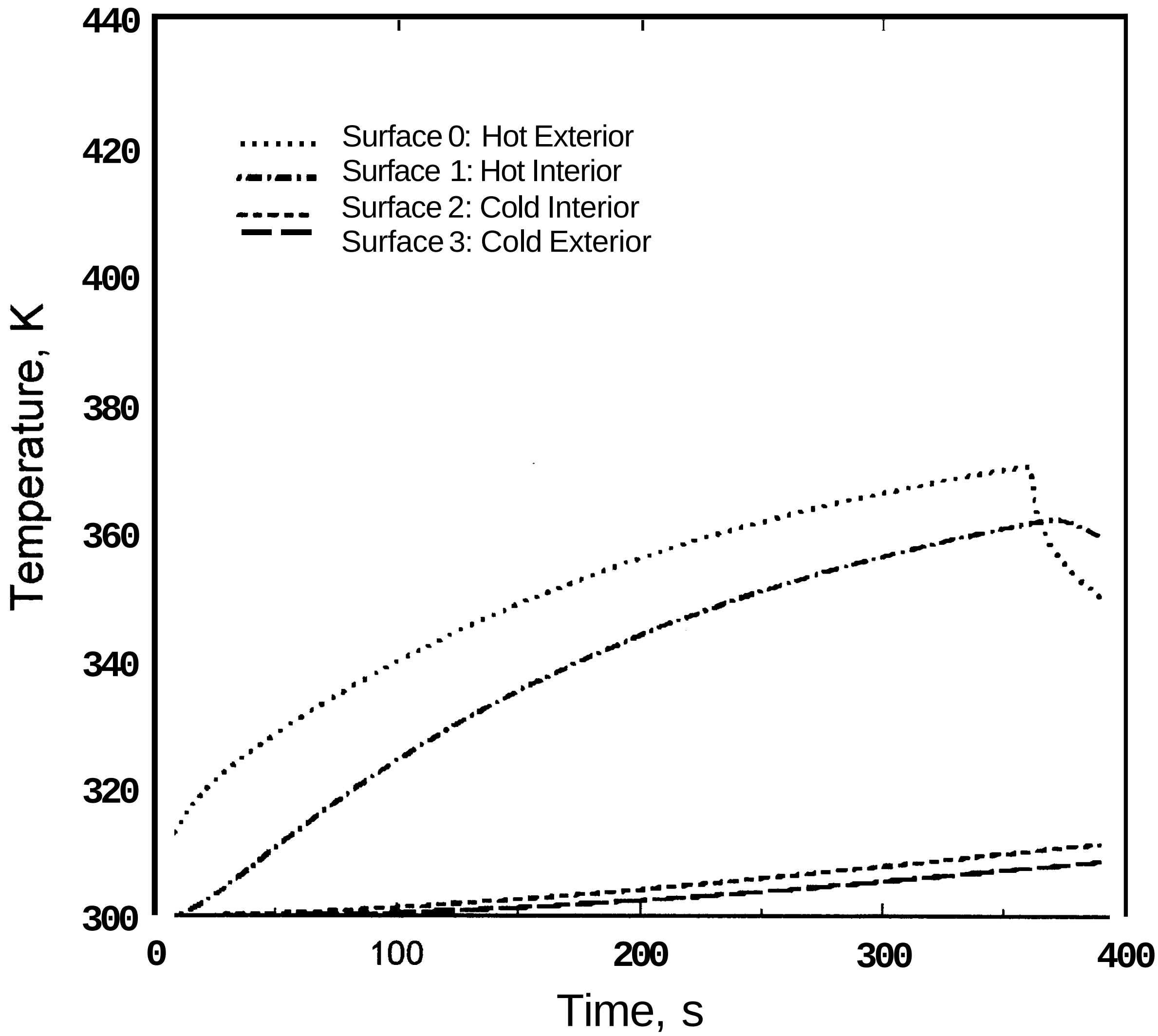


Figure 6b. **Same problem as Fig. 6a but with $\mathscr{F}=0.10$. Neither pane breaks.**

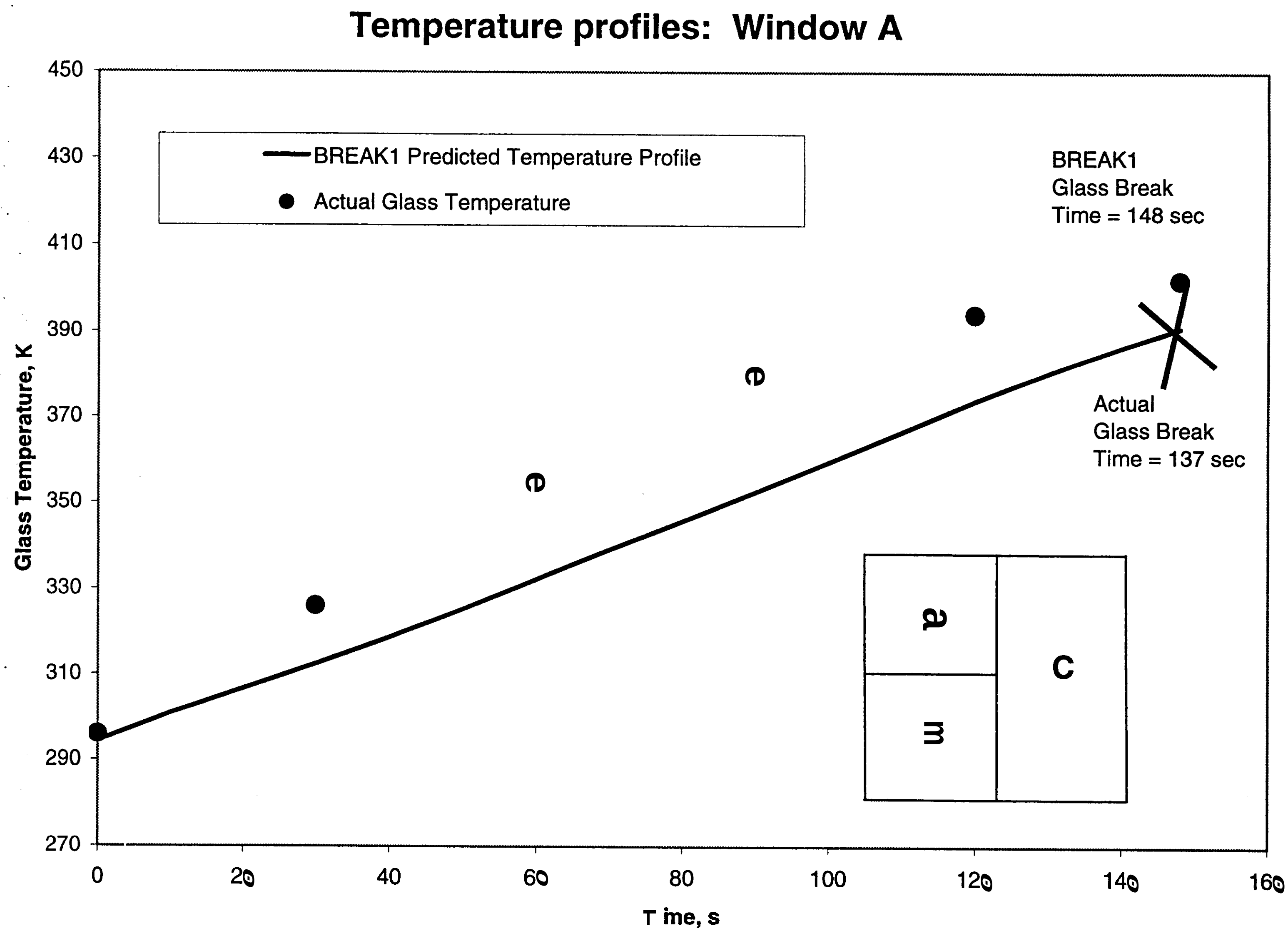
Thermal Cracking of Single Pane Glaring in Fires: Comparison with Models

by

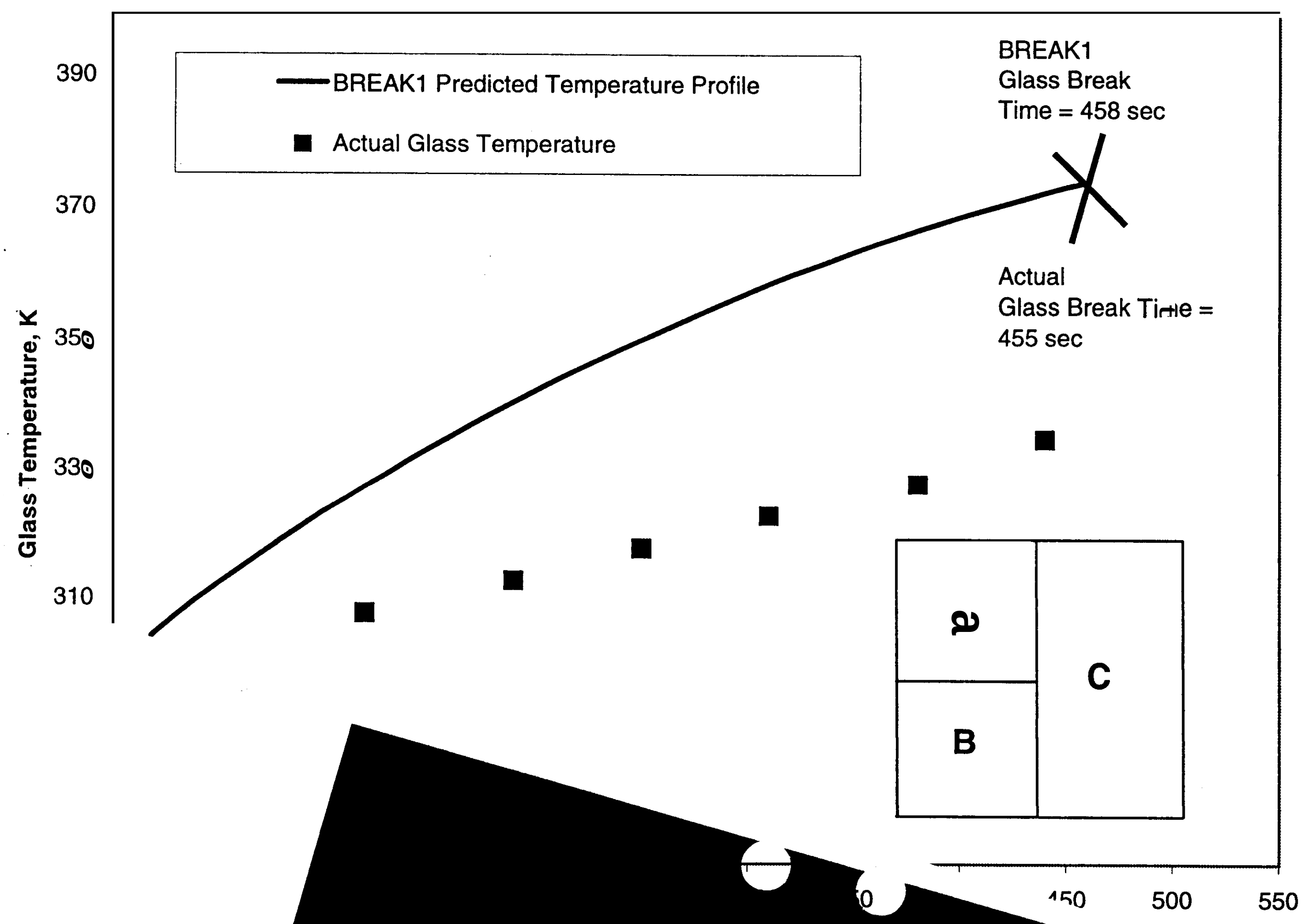
P. J. Pagni, T. J. Shields, G. W. H. Silcock and **M.** Flood

Abstract

Comparisons are presented here with thirty-three compartment fire experiments performed in the FireSERT Center laboratory at the University of Ulster. All the compartment fires were fueled by a square pool fire of mentholated spirits. Four pan sizes were used: 0.6, 0.7, 0.8, and 0.9m. In 14 experiments, the pan was placed in the center of the compartment and in 19 experiments the pan was placed in the rear corner of the compartment away from the windows and door. The compartment was a standard ISO room with a 0.4m wide by 2.0m door. Thermocouple trees were placed in the door and in the corner opposite the pan. Three windows occupied the long wall opposite the fire. Two 0.85m square windows were placed one on top of the other adjacent to a 0.85m wide by 1.9m high window. Glass temperatures were measured on all edges on the interior and exterior of each pane and under the edge shading. The compartment temperature field histories were compared with the predictions of the Harvard compartment fire model (FIRST). The times to appearance of the first crack in the window and the glass temperature histories were compared with the predictions of the Berkeley glass breaking model (BREAK1). Good agreement was obtained.


Temperature profiles: Window A
BREAK1 Predicted Temperature Profile
Actual Glass Temperature
BREAK1
Glass Break
Time = 148 sec
Actual
Glass Break
Time = 137 sec
e
e
a
m
c
Glass Temperature, K
450
430
410
390
370
350
330
310
290
270
0
20
40
60
80
100
120
140
160
T ime, s

Temperature Profiles: Window B



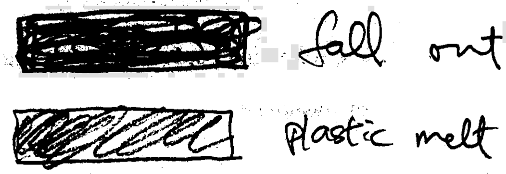
Temperature Profiles: Window C

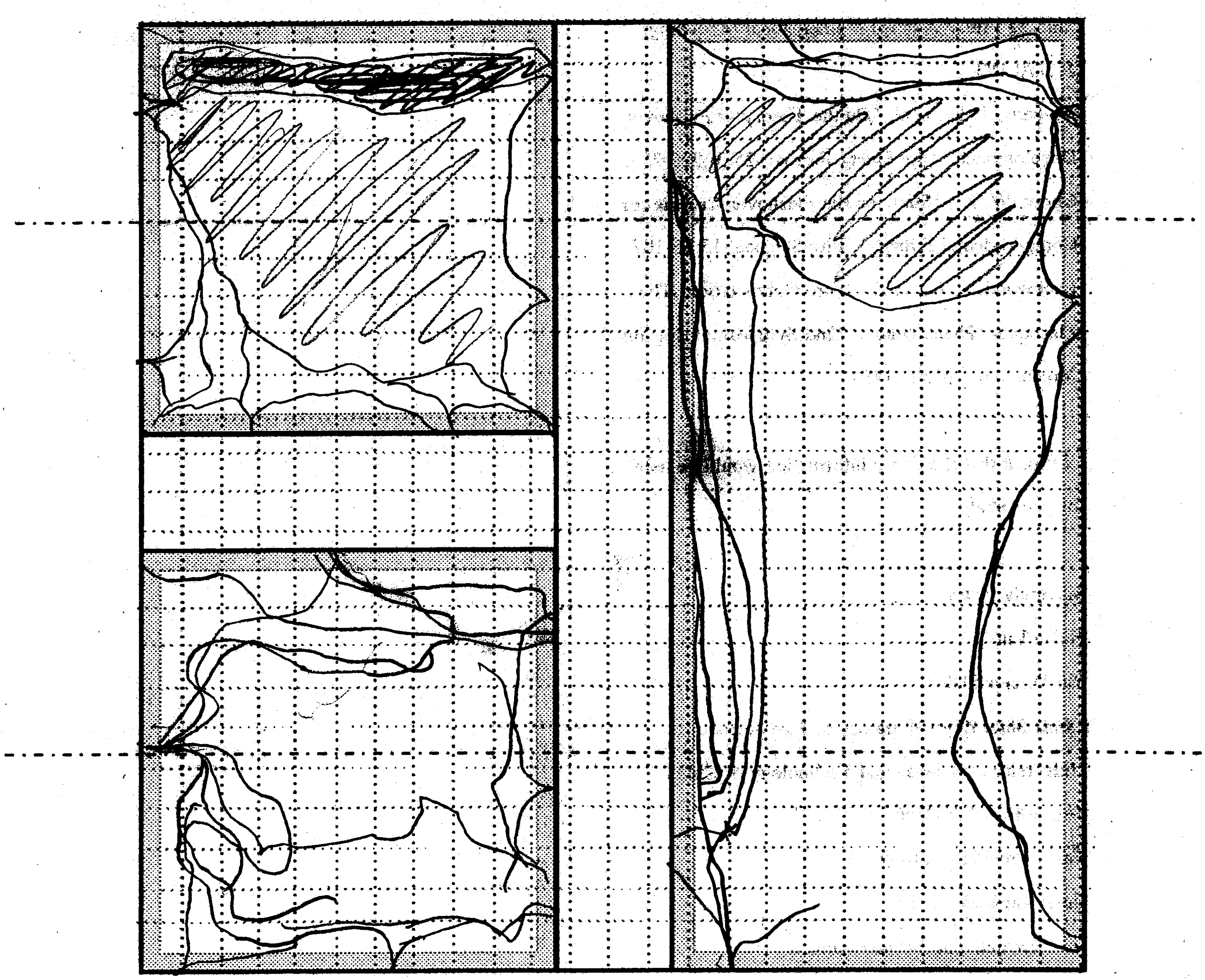
...ure Profile

BREAK1
Glass Break
Time = 307 sec

1/8

Test No. : LG LAM 3
Fire Position : CORNER
Tray Size : 800x800
Glazing Type: Laminated Glass





Needed Research

Criteria for Fall-out

Glass Properties

Heat Transfer Coefficients

In Summary We Need:

1) Better Residential Detection

2) To Recognize Glass Breaking as a Critical Part of Compartment Fire Modeling

3) Research on Glass Fall-out